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RF-MMW DIPOLE ANTENNA ARRAYS FROM LASER ILLUMINATED GaAs (U)

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Abstract (U)

(U) High resistivity photoconductive Gallium Arsenide (GaAs) can be used as elemental Hertzian dipole antenna arrays in which the time varying dipole current is produced by temporally modulating a laser (0.63μm) beam irradiance with a pulse width on the order of a picosecond or less. Electromagnetic emission from the dipole will result at a wavelength equal to the temporal modulation wavelength. Theoretical results will be presented for emitted RF-MMW radiant intensity from the array as a function of array geometry and laser pulse irradiation. These results will be compared to conventional RF-MMW sources.

Introduction (U)

(U) The majority of work in this approach is based upon previous similar research.[1,2] That focus was on the variable voltage bias steering properties of an experimental elemental dipole antenna array and concerned the 140Ghz to 1Thz portion of the spectrum. The approach considered within, will consider the more traditional RF-MMW application windows (i.e., <100Ghz), and will concentrate upon the quantitative magnitudes of power generation that can be achieved in order to determine the practicality of such an approach. In addition, some relevant results from the study of large aperture photoconducting antennas will also be applied.[3,4]

Theory (U)

(U) The dipole array emission is determined by (1) the antenna geometry, (2) the photoconductor electro-optical and transport parameters, and (3), the laser irradiance, pulse width and modulation method used for dipole excitation.

(U) The array will consist simply of an even number of parallel contact electrodes[1] (Au coated Ge) upon a p-type GaAs substrate consisting of a width, w, length, l, and inter-electrode spacing, d. Non-adjacent contacts will have a constant bias voltage applied, V, that spatially alternates positively and negatively in magnitude (see fig. 1).

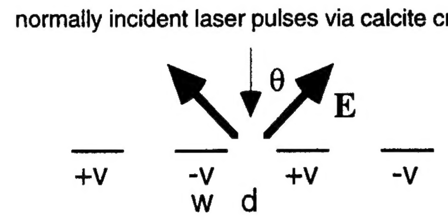

Fig. 1.

(U) The far-field electric field for a single column of elemental Hertzian dipoles, in which the modulation-emission wavelength is much greater than the dipole length, is given by the well known expression[5] in MKSA units (for symbolic notation, see list at end of document) as,

$$|\mathbf{E}(R,\theta)| = \frac{1}{2}\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2} i_{pk}\frac{d}{\lambda}\frac{\cos\theta}{R} \qquad (1)$$

The peak cosinusoidal photo-current at the GaAs surface generated by the unpolarized modulated laser illumination, assuming complete photo-absorption is,

$$i_{pk} = \frac{e}{hc}\left(\frac{4n}{(n+1)^2+\kappa^2}\right) g_{PH}\lambda_L P_L \qquad (2)$$

$$n = 3.93 \quad \kappa = 0.20$$

(U) The laser pulse width will be much less than the photo-induced free-carrier life-time of the GaAs. In this instance, it was found,[6] that the photoconductivity of GaAs is highly transient, and independent of the carrier life-time. The rise-time of the pulse will be essentially equal to the laser pulse width, and the carrier decay time will be approximated by the carrier transit time across the dipole, assuming the carrier life-time is longer than the carrier transit time.[7] This places constraints on the sweep-out bias electric field in order to maintain good pulse shape. For high electric fields and low modulation frequencies, assuming ohmic contacts, minimal carrier diffusion and no other detector time constant effects, the photoconductive gain in a high resistivity photoconductor is given by,[8]

$$g_{PH} = g_{PH,dc}\left[1 - g_{PH,dc}\left(1 - e^{-1/g_{PH,dc}}\right)\right]$$
$$g_{PH,dc} = \frac{\tau_c}{\tau_t} \rightarrow \frac{\tau_p}{\tau_t} = \frac{2\mu_c\tau_p V}{d^2} \quad (3)$$
$$\lambda_{MOD} = \lambda >> 2\pi c\tau_p$$

This sweep-out limited photoconductive gain saturates at 1/2. The slow dielectric relaxation component is not considered.

(U) For high resistivity GaAs, the photo-carrier diffusion length should be <1μm. Equation (3) should still be approxiimately valid. The following values will be assumed at 300K,

$$g_{PH,dc} = \frac{2\mu_c\tau_p V}{d^2} = 0.044 \rightarrow g_{PH} = 0.042 \quad (4)$$
$$\tau_p + \tau_t = T/3 \qquad \lambda_{MOD} = \lambda \geq 20\pi c\tau_p$$

From the original work on picosecond photoconductivity for p-type (Cr doped) GaAs with resistivities greater than 10^8ohm-cm,[6] the photo-carrier mobility can be estimated to be <150 cm^2/V-s. It was also found that this mobility was fairly constant until laser irradiances ~20MW/cm^2 - ~200MW/cm^2 (τ_p=1ps @1.06μm) were reached. Later results estimated a value of 220cm^2/V-s with a life-time of 300ps.[3,4] These mobility values are much less than the ~5,000cm^2/V-s[3,9] expected from carriers that are in thermal equilibrium with the lattice. It is believed that the electromagnetic emission is due to the drift of hot holes, which have much smaller mobilities than the equilibrium carriers.[3] The 220cm^2/V-s mobility value will be used in this analysis. This value, although low, is still ~7.5 times greater than that of radiation damaged Si on Sapphire and ~23% less than that of InP (~90ps life-time).[3] The high resistivity of GaAs permits relatively large bias electric fields with readily observable photoconductivity changes.

(U) The laser pulse assumed will be a hybrid mode-locked dye laser pumped at 80Mhz by a frequency-doubled YLF laser producing a wavelength of 0.63μm with pulse widths ranging from 150fs to 2.35ps.[1,10] The effective Gaussian beam radius and peak irradiance will be,

$$r_L = 1.5mm \quad I_L = 5W/cm^2$$
$$I(r) = I_L e^{-2r^2/r_L^2} \quad (5)$$

Dipole emission requires the laser irradiance to be cosinusoidally modulated at the RF-MMW emission wavelength. From Fourier transform theory,[1] the frequency content at the emission wavelength for a cosine modulated beam irradiance burst can be approximated by a periodic pulse pair where the amplitude of each pulse is 1/4 the amplitude of the peak cosine amplitude, and the spacing between pulses is,

$$T = \frac{1}{\nu_{MOD}} = \frac{1}{\nu} = \frac{\lambda}{c} \quad (6)$$

The number of periods in a burst is approximately the number of pulses in the pulse train. It is further assumed that any subsequent detection mechanism for this radiation has a spectral response optimized for the modulation-emission wavelength. The pulse pair spacing can be generated at the laser pulse repetition rate using a bi-refringent calcite crystal.[1] For a calcite plate with the plane of incidence cut parallel to its optical axis, the required thickness for a given pulse spacing is,[11]

$$z = \frac{cT}{|n_o - n_e|} = \frac{\lambda}{|n_o - n_e|} \quad (7)$$
$$n_o = 1.65 \quad n_e = 1.48$$

Assuming one reflection at each plate surface and no absorption, two pulses (the e-ray followed by the o-ray) separated by the bi-refringent delay with the same peak irradiance value of ~45% that of the laser peak irradiance value will be generated.

(U) The convolved laser power in equation (2) is for one dipole row formed from two contact lengths. For an even number of contacts, forming an odd number of dipole rows, a path difference will arise between rows forming a phase difference when the superposition of the row emitted electric fields is done.[5] The resultant electric field will be considered only for the planes normal and transverse to the dipole rows. When the laser irradiance beam is centered over the middle dipole row, it must be spatially convolved over all of the dipole rows, resulting in the following expression for the convolved power,

$$P_L = -P_o + 2\sum_{N_{odd}=1}^{1,3,5,\ldots} P_{\frac{N-1}{2}} \cos\left(\left(\frac{N-1}{2}\right)\Psi\right)$$

$$\Psi = \frac{2\pi}{\lambda}(d+w)\sin\theta$$

$$(e.g.\ 4\,contacts, 3\,dipole\,rows$$
$$P_L = P_o + 2P_1\cos\Psi)$$

$$P_k = P_o(A_k - B_k) \qquad k = 1,2,3,\ldots$$

$$A_k = \frac{erf\left(\frac{\sqrt{2}}{r_L}\left((k+\frac{1}{2})d + w\right)\right)}{2erf\left(\frac{d}{\sqrt{2}r_L}\right)}$$

$$B_k = \frac{erf\left(\frac{\sqrt{2}}{r_L}\left((k-\frac{1}{2})d + w\right)\right)}{2erf\left(\frac{d}{\sqrt{2}r_L}\right)} \tag{8}$$

$$P_o = \frac{\pi}{2}r_L{}^2 I_o erf\left(\frac{d}{\sqrt{2}r_L}\right) erf\left(\frac{l}{\sqrt{2}r_L}\right)$$

$$I_o \cong 4(0.45I_L) = 1.80I_L$$

$$(erf(x) = \frac{2}{\sqrt{\pi}}\int_o^x e^{-t^2}dt)$$

Reiterating, the P values assume complete cosinusoidal temporal modulation of the incident irradiance and are 1/2 the peak-peak convolved power incident upon the dipole elements. The d.c. modulation term does not contribute to the resultant RF-MMW electric field.

(U) The emitted RF-MMW beam irradiance (power/unit area) from the array received at a point in space in the theta direction can be found from the Poynting vector and equation (1) and equation (2) as,

$$I_{RF,MMW}(R,\theta) = \frac{1}{2}\left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2}|\mathbf{E}(R,\theta)|^2$$
$$= 9.29x10^{-5}\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2}\left[\frac{e}{hc}\frac{\lambda_L}{\lambda}\frac{d}{R}P_L\cos\theta\right]^2 \tag{9}$$

(U) The emitted RF-MMW beam radiant intensity (power/solid angle) from the array in the theta direction, assuming the distance from the array is much greater than the array dimensions, is,

$$J_{RF,MMW}(\theta) = I_{RF,MMW}(R,\theta)R^2 = \text{constant}$$
$$= 9.29x10^{-5}\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2}\left[\frac{e}{hc}\frac{\lambda_L}{\lambda}dP_L\cos\theta\right]^2 \tag{10}$$

Results (U)

(U) Figure (2) shows the required contact voltage as a function of contact separation (i.e. dipole length) for the condition described in equation (4) for 6Ghz and 94Ghz emission frequencies with laser pulse widths of 2.35ps and 150fs respectively.

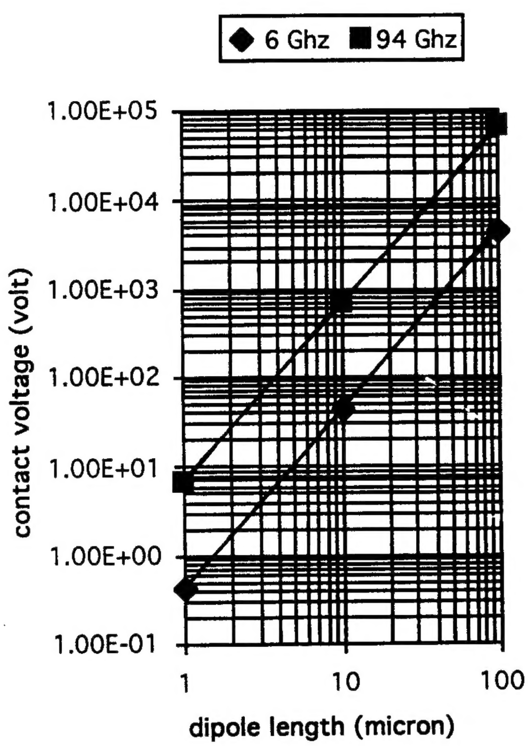

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Fig. 2. (U) Required contact voltage magnitude vs dipole length for 6 Ghz and 94 Ghz emission with a d.c. photoconductive gain = 0.044 and laser pulse widths of 2.35 ps and 150 fs respectively.

(U) The radiant intensity calculated from equation (10) at plus or minus forty-five degrees from the array normal for a dipole length of 10μm and a contact width and length of 25μm and 2mm respectively, is shown in figure (3) as a function of the number of contacts in the array.

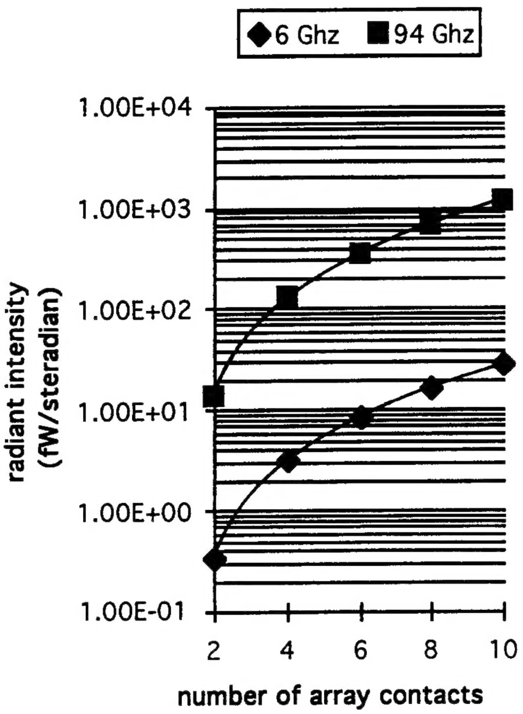

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Fig. 3. (U) Radiant intensity from array at forty-five degrees assuming a cosinusoidal burst for 6 Ghz and 94 Ghz emission (d=10μm, l=2mm and w=25μm).

Conclusion (U)

(U) The electric field strengths for the 10μm dipole length of figure (3) are >10^4V/cm. This value is typically one to two orders of magnitude greater than previously generated values.[1,2] This is attributed to the carrier transit time being made less than the pulse spacing, and is less severe for lower emission frequencies. Synchronously applying the bias voltages and laser pulse illumination may be necessary.

(U) Conventional 6Ghz and 94Ghz radars have average directional radiant intensity outputs, analogous to equation (10), of >35kW/sr and ~70W/sr respectively, with average power outputs of >75W and ~10mW respectively.[12] The values generated in figure (3) are in excess of 18 and 13 orders of magnitude less than the respective 6Ghz and 94Ghz conventionally cited values. It can also be seen from figure (3) that the array radiant intensity approaches an upper limit as the number of contacts is increased.

(U) From equation (10), the radiant intensity is proportional to the square of the incident laser power. A first order upper limit, similar to that of a previous calculation,[4] for the optimum (i.e., maximum) laser power can be made by assuming the maximum current flow through the center dipole row will occur when the reciprocal of the GaAs surface photoconductance is approximately equal to the parallel combination of the free-space and GaAs impedances, or,

$$\frac{1}{G_{PH}} \cong \frac{1}{k_\varepsilon^{1/2}+1}\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2} \qquad (11)$$

$$G_{PH} = e\mu_c\tau_p \frac{4n}{(n+1)^2+\kappa^2}\frac{\lambda_L}{hc}\frac{P_o}{d^2}$$

Using the previously defined parameter values and equation (8) yields the following,

$$P_o \cong \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \frac{\left(k_\varepsilon^{1/2}+1\right)}{e\mu_c\tau_p}\frac{\left((n+1)^2+\kappa^2\right)}{4n}\frac{hc}{\lambda_L}d^2$$

$$I_L = \frac{3.61x10^3}{cm^2}P_o = 0.28MW/cm^2 @ 6Ghz \qquad (12)$$

$$= 4.36MW/cm^2 @ 94Ghz$$

These values will increase somewhat since the index an extinction coefficient will both increase under intense illumination. It appears from equation (12), with unlimited laser power, that directional radiant intensities per modulation burst ~0.10mW/sr @ 6Ghz and ~1W/sr @ 94Ghz could be theoretically achieved, although the spatial dimensions of both the laser beam cross-section and dipole array, which determine the effective array emission area, would still be a limiting factor.

(U) From equation (5) and equation (12), the average energy density per laser pulse for the limiting case is 0.33μJ/cm^2. This value will vary as the square root of the contact voltage magnitude, or, linearly with dipole length.

(U) A better technique for temporal modulation of the laser pulse is needed. The required calcite crystal thickness becomes prohibitively large at lower frequencies.

(U) Small-scale applications may be feasibile for these types of arrays as RF-MMW sources if multiple cosinusoid burst integration is considered.

Symbolic Notation (U)

c speed of light

e electron charge

h Planck's constant

$\left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2}$ free - space impedance (377Ω)

λ_L laser wavelength

$\lambda = \lambda_{MOD}$ RF - MMW (modulation) wavelength

τ_p laser pulse width

τ_t carrier transit time

τ_c carrier life - time ($>> \tau_p$)

μ_c carrier mobility

g_{PH} photoconductive gain

n, κ GaAs index, extinction coefficient

$k\varepsilon \cong n^2 - \kappa^2$ GaAs dielectric constant

G_{PH} GaAs surface photoconductance

n_o, n_e Calcite o, e - ray index

R distance from center dipole row origin

P_L incident laser power

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